Chapter 5
Digesters, Gasifiers and Biorefineries: Plants and Field Demonstration

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Abstract In the present chapter an indication is given of the degree of industrialization reached so far by the biomass and waste conversion technologies described in Chaps. 3 and 4. Anaerobic digestion is a consolidated technology, which is reflected by the vast diffusion of waste water treatment plants. However, there is great potential for increased exploitation of this technology, especially by utilization of the diverse byproducts from the process. The future of anaerobic digestion is therefore closely related to the development of the biorefinery concept. As regards gasification, the flexibility of possible feedstock and the many varieties of syngas production routes lead to a large number of demonstration sites, with only few plants commercially in operation. These are summarized according to technology and geographical location.

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5.1 Biogas Installations and Applications

Biogas installations, processing agricultural substrates, are some of the most important applications of anaerobic digestion (AD) today. In Asia alone, millions of family-owned, small-scale digesters are in operation in countries like China, India, Nepal and Vietnam, producing biogas for cooking and lighting. Thousands of agricultural biogas plants are in operation in Europe and North America, many of them using the newest technologies within this area, and their number is continuously increasing.

Germany is certainly the European country in which in the last ten years anaerobic digestion had the greatest impulse, particularly in the animal farming (zootechnic) field. There are about 2,700 existing plants with an electric power installed of about 665 MW. About 94% of biogas plants operate in co-digestion mode (i.e. digesting different substrates together), treating zootechnic effluents together with other organic substrates, like agro-industrial residues, domestic wastes, residues of food processing industry, energy crops (maize, corn, sugar beet, potatoes etc.) and farming residues. Very important for biogas development has been the policy of promotion adopted by the German government; they fixed a price payable for electric energy from biogas plants (a so-called feed-in tariff, 21.5 c€/kWh at the time of writing) guaranteed for a 20 year period, in addition to a contribution on the investment. In the last years the importance of anaerobic treatment of the organic fraction of municipal solid waste (OFMSW) together with other organic industrial wastes and with zootechnic sewage (in co-digestion) is growing consistently [1].

In Sweden there are seven farm installations and 10 centralized plants; they mainly use a co-digestion process fed with OFMSW and agro-industrial wastes. In this country the utilization of biogas for vehicle fuel is widely promoted: biogas is available at refill stations in 24 localities in the south of Sweden. There are at least 4,000 vehicles running on biogas, among which also buses of local authorities [2]. The promotion of biogas as fuel for vehicles, mostly used also in Austria, Germany, Denmark and Switzerland calls for specific indications of quality, which differ little among the countries (see Chap. 10).

In Denmark, there are currently 20 centralized co-digestion plants that treat annually about 1,100,000 t of zootechnic sewage and 375,000 t of organic industrial residues and OFMSW.

In Europe [3, 4] there are about 130 AD installations treating OFMSW (from separate garbage collection, or from mechanical selection downstream) and/or organic industrial residues, with a capacity of about 3.9 million tons of treated waste per year.

The 2010 EurObserv'ER estimates a biogas production of about 8,700 ktep in EU Countries.

The organic waste produced annually in the countries of the European Union amounts to about 2,500 million tons, of which about 60% is constituted of animal farming effluents and the remaining comes from OFMSW, agro-industrial residues and municipal sewage sludge [5].

In Italy there are still only a few biogas plants operating on a mixture of several residues: seven of these are centralized plants and treat also sewage sludge, agro-industrial effluents, particularly wastewater from the olive industry, and OFMSW. Another 100 plants on farm-scale are operating on animal farming effluents, particularly from pig farms; some plants, of recent construction, treat also dedicated energy crops.

5.1.1 The Biorefinery Concept

As a result of further development in digestate treatment technology it could become possible to step up from common AD, bio-ethanol and bio-diesel plants to next-generation and sustainable bio-refineries.

The bio-refinery concept proposes a potentially complete exploitation of the vegetable biomass to obtain not only energy products, but also materials and chemical substances with high additional value. It represents one of the most important developments towards changing the current production of goods and services based on fossil resources to a new economy based on the utilization of biological raw material and renewables. The realization of this radical approach needs new advances in research and development, where technical, physical, chemical and biological sciences work in synergy, playing a leading role in the generation of future industries [7, 8]. Through the development of biorefinery systems, the term "waste biomass" should become obsolete in the medium term [9]: for exemple, dry residues from wood industry are available as fuel or for the paper and cardboard industry, wet biomass waste from food cultivation represents an organic chemical pool, from which fuels, chemicals and biomaterials can be produced, see Fig. 5.1. An example of bio-refinery is very schematically explained in Fig. 5.2 below, where the water separated from the digestate is used together with the biogas for the growth of algae. Algae consume CO_2 and nutrients, thereby concentrating the methane content of biogas and depurating waste water. The carbon dioxide coming from the burning downstream of the methane produced can also be fed to the algae.

Apart from the benefits in terms of resource utilization, the development of biorefineries could slow down or even reverse the decline of agricultural employment, have a positive impact on farm income, counteract land abandonment in marginal regions and land conversion from agricultural to other uses.

5.1.2 Bioethanol from Waste

A colossal market that could be tapped into in order to generate this new agricultural revolution, is represented by the need for liquid fuels. Compared to gaseous energy carriers, liquid fuels are easier to store and transport and have greater energy density, making them ideally suited for mobile applications. In this context,

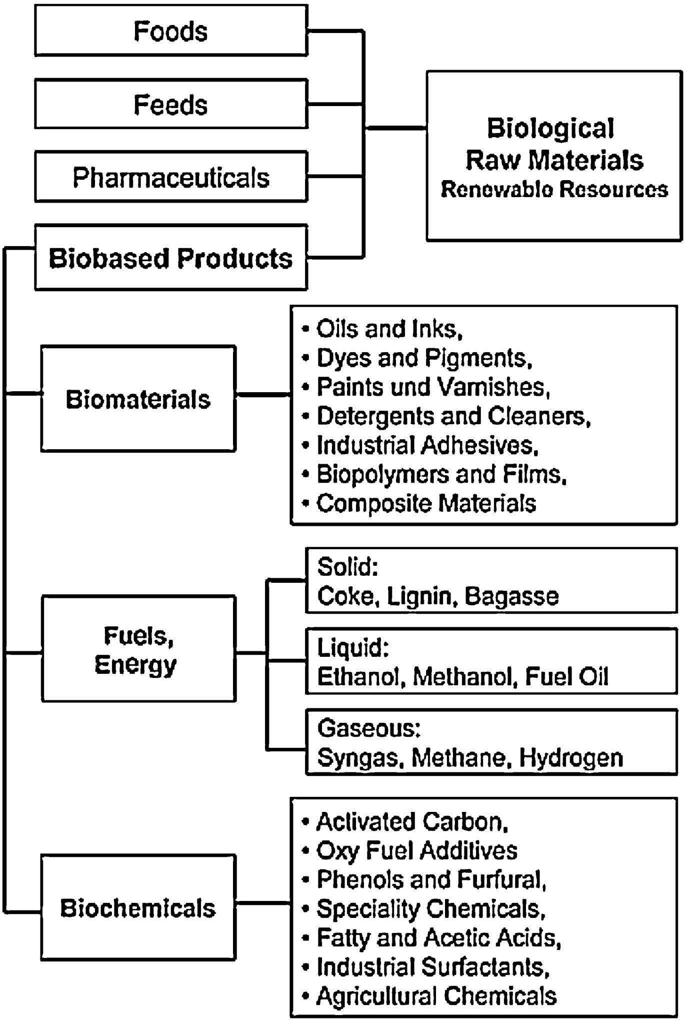
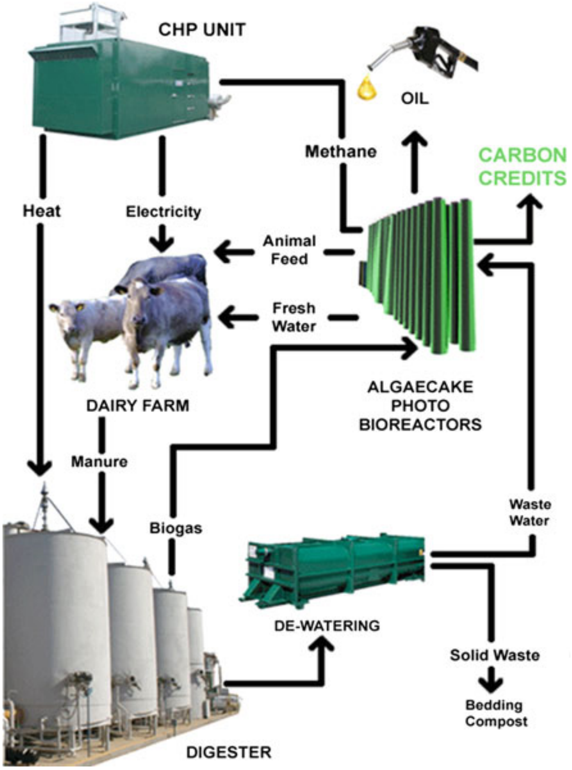


Fig. 5.1 Products and product classes derived from biological raw materials [6]

the most promising liquid fuel that can be derived from biomass and organic waste is ethanol. Ethanol is an alcohol conventionally made through the fermentation of plant sugars from agricultural crops and biomass resources. The most common agricultural crop currently utilized for ethanol production is corn: in the USA 11 billion gallons of corn-based ethanol were produced in 2009 [10]. Only a portion of the feedstock is needed for ethanol production and the remainder can be used for animal feed, corn oil, or other products. However, this implies the sacrifice of arable land—which could be used for e.g. food production—for the sake of energy capture through growing virgin crops. Again, exploitation of resources already

Fig. 5.2 Example of a biorefinery



utilized, but not completely spent, to yield the same product, is preferable, and reduces the resultant flow of waste to be disposed of.

Biogas from anaerobic digestion, not only because of its methane content but also through the carbon dioxide content, heat, and digestate produced, can provide process energy and available nutrients for liquid biofuel production as well, increasing the total efficiency of conversion, lowering global costs and greenhouse gas emissions thanks to the source of fuel used. Besides, the wastes from biofuel production processes, such as exhausted algae or glycerine, can be fed into the digester again, thus maximizing material recycle, and closing the energy and nutrients balance. Policy makers and researchers are still exploring the opportunities for integrating ethanol or bio-diesel production and anaerobic digestion plants. Some bio-refinery pilot projects have been implemented in Europe [11] and around the world. At least a couple of such plants are being built in North America at the time of writing, one in Ontario and another in Nebraska.

The integration between anaerobic digestion treatment and the ethanol production process can lead to several advantages in both environmental and energetic fields: in fact, anaerobic digestion processes can both supply the energy and substrate requests for ethanol fermentation, and contribute to the reutilization of distillage wastes, thus minimizing ecological footprint.

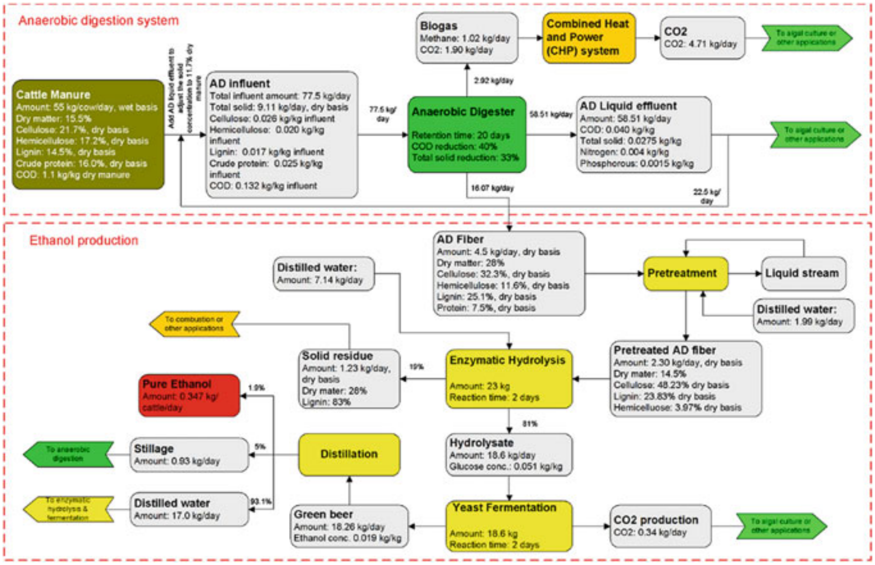

Anaerobic digestion system
Cattle Manure
Amount: 55 kg/cow/day, wet basis
Dry matter: 15.5%
Cellulose: 21.7%, dry basis
Hemicellulose: 17.2%, dry basis
Lignin: 14.5%, dry basis
Crude protein: 16.0%, dry basis
COD: 1.1 kg/kg dry manure
Add AD liquid effluent to adjust the solid concentration to 11.7% dry manure
AD influent
Total influent amount: 77.5 kg/day
Total solid: 9.11 kg/day, dry basis
Cellulose: 0.026 kg/kg influent
Hemicellulose: 0.020 kg/kg influent
Lignin: 0.017 kg/kg influent
Crude protein: 0.025 kg/kg influent
COD: 0.132 kg/kg influent
77.5 kg/ day
Anaerobic Digester
Retention time: 20 days
COD reduction: 40%
Total solid reduction: 33%
2.92 kg/day
Biogas
Methane: 1.02 kg/day
CO2: 1.90 kg/day
Combined Heat and Power (CHP) system
CO2
CO2: 4.71 kg/day
To algal culture or other applications
58.51 kg/day
AD Liquid effluent
Amount: 58.51 kg/day
COD: 0.040 kg/kg
Total solid: 0.0275 kg/kg
Nitrogen: 0.004 kg/kg
Phosphorous: 0.0015 kg/kg
To algal culture or other applications
16.07 kg/day
22.5 kg/ day
Ethanol production
AD Fiber
Amount: 4.5 kg/day, dry basis
Dry matter: 28%
Cellulose: 32.3%, dry basis
Hemicellulose: 11.6%, dry basis
Lignin: 25.1%, dry basis
Protein: 7.5%, dry basis
Pretreatment
Liquid stream
Distilled water:
Amount: 1.99 kg/day
Pretreated AD fiber
Amount: 2.30 kg/day, dry basis
Dry mater: 14.5%
Cellulose: 48.23% dry basis
Lignin: 23.83% dry basis
Hemicelluose: 3.97% dry basis
Distilled water:
Amount: 7.14 kg/day
To combustion or other applications
Solid residue
Amount: 1.23 kg/day, dry basis
Dry mater: 28%
Lignin: 83%
19%
Enzymatic Hydrolysis
Amount: 23 kg
Reaction time: 2 days
81%
Hydrolysate
Amount: 18.6 kg/day
Glucose conc.: 0.051 kg/kg
Pure Ethanol
Amount: 0.347 kg/ cattle/day
1.9%
Stillage
Amount: 0.93 kg/day
5%
Distillation
To anaerobic digestion
To enzymatic hydrolysis & fermentation
Distilled water
Amount: 17.0 kg/day
93.1%
Green beer
Amount: 18.26 kg/day
Ethanol conc. 0.019 kg/kg
Yeast Fermentation
Amount: 18.6 kg
Reaction time: 2 days
CO2 production
CO2: 0.34 kg/day
To algal culture or other applications

Fig. 5.3 Mass balance of integrated anaerobic digestion and ethanol production system per day per cow [15]

Ethanol fermentation is an intensive energy and water consuming process, that produces much distillage waste: 8–15 litres per single litre of ethanol produced [12]. A small part (15–30%) of this waste can be recycled in the ethanol fermentation process, and the residues can be fed into an anaerobic digester. Sometimes an aerobic post-treatment is needed as well [13]. In recent studies [14], authors have developed an ethanol-methane coupled fermentation system with the aim of obtaining high ethanol fermentation performance as well as economical and environmental benefits, by the reutilization of waste distillage and of methane generated on-site.

Other authors have focused their studies on the logistic availability of agricultural wastes for the ethanol production process, in order to ensure stable cellulosic feeding for the fermentation, instead of that from seasonal grain-based crops, significantly reducing transportation and storage cost and avoiding competition with food.

Yue and co-authors [15], using the solid part of digestate from the anaerobic digestion of cow manure (also called AD fibre), obtained a glucose conversion rate of nearly 90% and an ethanol fermentation yield of 72%, after optimizing the operating conditions of alkaline pre-treatment of the AD fibre and of the following enzymatic hydrolysis. From first experiences, they have calculated, through a mass balance reported in Fig. 5.3, that 1.02 kg of methane and 0.347 kg of ethanol can be produced daily from a cow, without addition of distilled water. They have also demonstrated that the solid part of digestate from cattle manure is of similar quality to other cellulosic feedstock like switchgrass and corn stover in terms of glucose conversion and ethanol yield. Moreover, AD fiber is characterized by small particle sizes, which allows to remove the feedstock grinding unit, that

Table 5.1 Overview of biomass gasification plants and systems currently running in the world [26, 27]

Country	Capacity (MWth)	Technology	Location	Note
Austria	8	TUV FICFB CHP demonstration	Güssing	2.0 MWe + 4.5 Wth Heat, 50 t/day of wood chips from forestry
	2	Down-draft CHP at demonstration	Wr. Neustadt	0.5 MWe + 0.7 MWth Heat, 12 tons/day of wood chips from forestry
Denmark	5	VØlund up-draft CHP demonstration	HarbØre	1.5 MWe + 2 MWth Heating
	0.7	Viking 2-stage gasification and power generation	Lyngby	Electrical efficiency could exceed 35%
	3.125 and 0.833 (Japan)	TKEnergi 3-stage, gasification process demonstration	Gjøl	Two gasifiers were designed at a cost of € 3.1 million (Denmark) and € 1 million (Japan) and the thermal efficiencies are 56% and 60 while the electrical efficiencies are estimated to be 32 and 24%, respectively
	30	Carbona Renugas fluidized bed CHP demonstration	Skive	5.5 MWe, and 11.5 MWth district heat
Finland	4–5	Bioneer up-draft gasifiers	8 in Finland and one in Sweden	In operation for over 20 years
	60 (50–86)	Foster Wheeler Energy CFB co-firing plant	Lahti (Ruien, Belgium)	The Foster Wheeler Energy Oy has developed CFBG process that was successfully deployed at a paper mill in Pietersaari and for co-firing at Lahti and a BFB gasifier for aluminium and energy recovery in Varkaus. A completely new, 160 MWth CFB BMG plant is now in the design phase
	40	Foster Wheeler Energy fluidized bed metal recovery gasifier	Varkaus	
	7	NOVEL Updraft demonstration	Kokemäki	This CHP facility employs low-temperature waste heat from the plant to dry wood fuels to about 20% moisture. The design power output is 1.8 MWe and the district heat output is 4.3 MWth (3.1 MWth without boiler). The overall investment cost is € 4.5–5 million

(continued)

Table 5.1 (continued)

Country	Capacity (MWth)	Technology	Location	Note
Germany	130	Commercial waste to methanol plant (Fixed bed + Pressurized entrained flow)	Schwarze Pumpe	The largest renewable waste gasification plant in the world has been built and operated for nearly 20 years. Feed materials is waste mix brown coal
	100	Lurgi CFB gasifier firing cement kiln	Rüdersdorf	The successful Lurgi CFBGs are the 100 MWth waste gasification plant to fire cement kilns
	0.5	Fraunhofer Umsicht CFB pilot plant	Oberhausen	Based on tests conducted at feed rates of 70–120 kg/h of wood and for over 1,600 h, developments are underway to build a 1–5 MWth CHP and a 5 MWth demonstration BMG plant
	1	CHOREN Carbo-V 2-stage entrained pilot plant	Freiberg	The resulting tar-free synthesis gas from the 1 MWth capacity pilot plant tests has been converted to fuels by F-T and methanol synthesis
	3–5	Future Energy pyrolysis/ entrained flow GSP gasifier	Freiberg	It produces a tar- and CH_4-free raw gas, with C-conversion > 99%, at very short residence times (seconds) and at high throughput rates
Italy	15	TPS CFB RDF plant	Greve in Chianti	TPS Termiska Processer of Sweden has built the first large scale TPS CFB plants in Greve, in the Chianti district. The plant has operated intermittently with RDF pellets and it is currently shutdown with an indefinite future.
	0.5;1.2	ENEA CFBG pilot plant	Trisaia	Described in Chap. 4

(continued)

Table 5.1 (continued)

Country	Capacity (MWth)	Technology	Location	Note
Netherlands	85	AMER/Essent/Lurgi CFB gasification co-firing plant	Geertruidenberg	Feedstock for this plant is demolition wood and the resulting fuel gas is co-fired in a 600 MWe pulverised coal boiler
	250 (35 MWe from biomass)	Biomass co-gasification Shell entrained coal gasification plat	Willem-Alexander Centrale	The biomass materials included sewage sludge, chicken manure, wood
	3	CFBG Plan	Tzum	The leading small-scale gasification system supplier in Netherlands, HoST also has built a 3 MWth chicken litter gasifier in Tzum NL, which is currently being commissioned
		Several pilot plants at ECN	Petten	Torrefaction, a 5 kg/h allothermal gasifier, testing and evaluation of the TREC granular bed filter, development of lab-scale integrated BMG system for SNG production, and the OLGA gas clean-up process which has recently completed 700 h of operation during a long-duration test at 0.5 MWth scale
New Zealand	2	Page Macrae updraft BMG plant	Tauranga	Page MaCrae Engineering Ltd is operating a 2 MWth commercial, updraft co-firing BMG plant, using the wood residues generated in a plywood mill to supply heat for manufacturing plywood. Based on the same technology, Page MaCrae is planning to manufacture an 8 MWth BMG plant

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Table 5.1 (continued)

Country	Capacity (MWth)	Technology	Location	Note
Sweden		Bioneer up-draft BMG plant		Some of the early biomass gasification plants were built in Sweden. The 20 MWth FWE/Ahlstrom CFB plant at Norrsundet and the 30 MWth plant at Karlsborg are still in operation
	30	Foster Wheeler Energy CFBG	Karlsborg paper mill	
	20	Foster Wheeler Energy CFBG	Norrsundet paper mill	
	30	Gotaverken CFBG	Södracell paper mill	Fuelled by bark and wood wastes
	18	Bioflow/Sydkraft/Foster Wheeler Energy CHP demonstration at	Värnamo	The most significant technical accomplishment in biomass gasification is the successful demonstration of the pressurized, CFB Bioflow BMG in Värnamo, supplied by Ahlstrom/FWE and Sydkraft. The 18 MWth capacity plant was operated at 18 bar pressure. The raw gases were cleaned without condensation employing candle filters and successfully combusted in a closely integrated Typhoon gas turbine to generate 6 MWe and 9 MWth heat for district heating
Switzerland	0.2	Pyroforce down draft BMG system	Spiez (scale-up to 1 MWe plant in Austria)	The plant employs a Pyroforce gasifier, based on the KHD (Kloeckner Humbolt Deutz) high temperature gasification process and a dry gas cleaning system
UK	100 KWe	Rural Generation downdraft BMG system	Northern Ireland	The 100 kWe Brook hall plant has exceeded 15,000 h of operation
	Up to 250 KWe	Biomass Engineering Ltd., down draft BMG CHP systems	Northern Ireland	Biomass Engineering continues progress with manufacturing six small (250 kWe) commercial CHP units while three other units are in operation or commissioning

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Table 5.1 (continued)

Country	Capacity (MWth)	Technology	Location	Note
	Up to 300 KWe	Exus Energy down draft BMG CHP systems	Northern Ireland	BEDZED a 100 kWe CHP installation has completed 5000 h of operation in total, but problems have been reported recently. A 300 kWe CHP plant is to be installed in a limekiln operation. The Blackwater Valley plant will be a redesigned for a 200 kWe CHP plant. The company is reportedly restructuring and the status of these projects is unclear at this time
	7 MWe	Charlton Energy rotary kiln waste gasification	Gloucestershire	A 7 MWe, rotary kiln gasifier CHP plant is operating in Gloucestershire. The plant will include Eco-tran equipment, reciprocating engines and it will use agricultural and forestry biomass as feed materials. Support comes from Capital Grant plus Renewable Obligation. Revenues will be derived from heat sale to nearby sawmill for drying wood
	2 MWe	Compact Power two-stage waste gasification plant	Bristol	This plant has completed three years of commercial operation on wastes with excellent emissions performance
USA	Up to 120	Primenergy gasification/ combustion systems	6 in USA and 1 in Italy	1 plant at Tulsa (Oklahoma), feed material: various, 3 plants at Stuttgart (Arkansas) feed material: ricehusks, a at Rossano, Italy feeded with olive waste, one at Philadelphia (Pennsylvania) feede with biosolids

(continued)

Table 5.1 (continued)

Country	Capacity (MWth)	Technology	Location	Note
	Up to 22 KWe	Community Power Corporation small modular down-draft gasification systems		22 kWe gasification gas engine system has been demonstrated at Aliminos in the Philippines with coconut shells. 15 Similar units were also tested and being demonstrated in the USA for a variety of heating applications
		FERCo SilvaGas dual CFBG Process RENUGAS fluidized bed BMG Process FERCo SilvaGas dual CFBG Process RENUGAS fluidized bed BMG Process		The notable biomass gasification processes that have been scaled up to near commercial scale and operated with varying degrees of success are the Battelle/FERCO dual CFB SilvaGas process and the Renugas® Process, developed by IGT/GTI and Carbona. It is anticipated that these processes and others may play an important role in the evolving concepts for biorefineries of the future

orresponds to 20% of capital investment costs on feedstock storage and handling within the production facility, greatly improving the efficiency and cost-effectiveness of ethanol production [16].

With the coupling of anaerobic digestion and bioethanol production, biomass utilization can be optimized to the highest level [17], because hemi-cellulose is consumed better through methane fermentation, avoiding problems associated with pentose fermentation during the following ethanol production, for which cellulosic matter is available.

Once produced, bio-ethanol can be converted in situ to hydrogen-rich gas by a simple reforming process, and thus, it is considered a promising fuel for high-temperature fuel cells (HTFCs), which utilize the high-temperature heat deriving from their operation for fuel conditioning. Although the HTFC is known for its high tolerance of organic compounds, some impurities resulting from the combined digestion-fermentation process, such as sulfur compounds, halogens, and siloxanes, deteriorate its performance. Bio-ethanol always contains some impurities such as diethyl amine, acetic acid, methanol, and propanol with concentrations in the range of 200 ppm up to 0.9%. These impurities in bio-ethanol may influence the performance of HTFCs, but in different ways and to different degrees [18–25]: methanol and diethyl amine enhance the activity of the reforming catalyst, whereas propanol and acetic acid were found to decrease the activity of the catalyst.

5.2 Gasifiers Plants and Demonstration Projects

Of the biomass energy conversion processes, gasification offers the benefit of being able to convert many different types of biomass feed stocks and wastes to produce a fairly uniform fuel gas, largely renewable, that can readily displace fossil fuels. Many of the developed countries in the world have set a variety of environmental targets to secure sustained supply of renewable energy. The plans to attain these targets include conspicuous utilization of biomass, creating thereby the right conditions for the development and widespread implementation of gasification. A variety of national action plans, directives, and multi-year RD&D programs are being implemented to expedite the development and commercialization of efficient and environmentally sound biomass energy conversion technologies. This is reflected in the biomass gasifier demonstration projects and commercial plants taking place in the member countries of Task 33 of the International Energy Agency's area of interest on Bioenergy, which are summarized and described in Table 5.1 [26].

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